Measurement of Coherent Emission and Linear Polarization of Photons by Electrons in the Strong Fields of Aligned Crystals

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We present new results regarding the features of high energy photon emission by an electron beam of 178 GeV penetrating a 1.5 cm thick single Si crystal aligned at the Strings-Of-Strings (SOS) orientation. This concerns a special case of coherent bremsstrahlung where the electron interacts with the strong fields of successive atomic strings in a plane and for which the largest enhancement of the highest energy photons is expected. The polarization of the resulting photon beam was measured by the asymmetry of e^+e^- pair production in an aligned diamond crystal analyzer. By the selection of a single pair the energy and the polarization of individual photons could be measured in an the environment of multiple photons produced in the radiator crystal. Photons in the high energy region show less than 20% linear polarization at the 90% confidence level.

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I. INTRODUCTION

Interest in the generation of intense, highly polarized high energy photon beams [1, 2] comes in part from the need to investigate the polarized photo-production mechanisms. For example, the so-called "spin crisis of the nucleon" and its connection to the gluon polarization has attracted much attention [3]. Future experiments will require intense photon beams with a high degree of polarization. The radiation emitted by electrons passing through oriented single crystals is important for these purposes. The coherent bremsstrahlung (CB) of high energy unpolarized electrons is a well established and widely applied technique for producing intense photon beams with a high degree of linear polarization. The coherence arises in this case due to crystal effects which become pronounced when the electron incidence angle with respect to a major plane is small. The resulting CB radiation differs from incoherent bremsstrahlung (ICB) in an amorphous target in that the cross section is substantially enhanced and relatively sharp coherent peaks appear in the photon spectrum. The position of these peaks can be tuned by adjusting the electron beam incidence angle with respect to the major plane of the lattice.

There is another less well known method of producing greater enhancement as well as a harder photon spectrum than the CB case. This is achieved by selecting a very specific electron incident angle with respect to the crystal. If the electron beam is incident very close to the plane (within the planar channelling critical angle) and also closely well aligned to a major axis (but beyond the axial channelling critical angle), then the electron interacts dominantly with successive atomic strings in the plane. This orientation had been aptly described by the

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term "String-Of-Strings" (SOS) by Lindhard, a pioneer of beam-crystal phenomena [4]. The NA43 Collaboration has studied the radiation emitted by electrons incident in the SOS orientation. The reference [5] and references therein are an account of this study, as well as many other related effects. There remained the issue of the polarisation of the SOS radiation. Polarisation measurements have been reported [6] which could be consistent with substantial polarisation of the hard component of SOS radiation. However the ability to distinguish clearly a single photon spectrum from the total radiated energy spectrum was not yet developed for that measurement. In this paper, a new study of SOS-produced high energy photon beams is reported in which we were able to study the beam on a photon-by-photon basis, and measure both the enhancement and the linear polarisation as a function of photon energy.

II. THEORETICAL DESCRIPTION

The CB mechanism produces linearly polarized photons in a selected energy region when the crystal type, its orientation with respect to the electron beam, and the electron energy are appropriately chosen. In the so-called point effect (PE) orientation of the crystal the direction of the electron beam has a small angle with respect to a chosen crystallographic plane and a relatively large angle with the crystallographic axes that are in that plane. For this PE orientation of the single crystal only one reciprocal lattice vector contributes to the CB cross section. The CB radiation from a crystal aligned in this configuration is more intense than the ICB radiation in amorphous media and a high degree of linear polarization can be achieved [7]. The PE orientation of the crystal was used in a previous NA59 experiment, where a large linear polarization of high energy photons was measured. The photons had been produced by an unpolarized electron beam. The conversion of the linear polarisation to circular polarization induced by a birefringent effect in an aligned single crystal was also studied [8, 9].

The character of the radiation, including its linear polarization, is changed when the direction of the electron (i) has a small angle with a crystallographic axis and (ii) is parallel with the plane that is formed by the atomic strings along the chosen axes. This is the so-called SOS orientation. It produces a harder photon spectrum than the CB case because the coherent radiation arises from successive scattering off the axial potential, which is deeper than the planar potential. The radiation phenomena in single crystals aligned in SOS mode have been under active theoretical investigation since the NA43 collaboration discovered, for the first time, two distinct photon peaks, one in the low energy region and one in the high energy region of the radiated energy spectrum for about 150 GeV electrons traversing a diamond crystal [10]. It was established that the hard photon peak was a single photon peak. However, the radiated photons were generally emitted with significant multiplicity in such a way that a hard photon would be accompanied by a few low energy photons. It will be seen later that two different mechanisms are responsible for the soft and the hard photons. In the former case, it is planar channelling (PC) radiation, while in the latter case, it is SOS radiation.

The issue of the polarisation of SOS radiation also came into question. Early experiments with electron beams of up to 10 GeV in single crystals showed a smaller linear polarization of the more intense radiation in the SOS orientation than in the PE orientation (see [11] and references therein). The first measurements of linear polarization for high energy photons ($E_\gamma \approx 50 - 150\,\mathrm{GeV}$) were consistent with a high degree of linear polarization of the radiated photons [6]. At this stage the theoretical prediction of the SOS hard photon polarisation was unresolved. However, it was clear that the photons emitted by the PC mechanism would be linearly polarised. This experiment therefore could not be considered conclusive, as the polarimeter recorded the integral polarisation for a given radiated energy, which was likely to have a multiphoton character. The extent to which pile-up from the low energy photons perturbed the high energy part of the total radiated energy spectrum was not resolved. These results therefore required more theoretical and experimental investigation.

A theory of photon emission by electrons along the SOS orientation of single crystals has since been developed. The theory takes into account the change of the effective electron mass in the fields due to the crystallographic planes and the crossing of the atomic strings [12]. The authors show that the SOS specific potential affects the high energy photon emission and also gives an additional contribution in the low energy region of the spectrum. In Refs. [13, 14] the linear polarization of the emitted photons was derived and analysed for different beam energies and crystal orientations. The predicted linear polarization of hard photons produced using the SOS orientation of the crystal is small compared to the comparable case using the PE orientation of the crystal. On the other hand, the additional soft photons produced with SOS orientation of the crystal are predicted to exhibit a high degree of polarization.

The emission mechanism of the high energy photons is CB connected to the periodic structure of the crystal [7].

The peak energy of the CB photons, E_γ, is determined from the condition (the system of units used here has $\hbar = \mathrm{c} = 1$),

$$\frac{1}{|q_{\|}|} = 2\lambda_c \gamma \frac{E_0 - E_\gamma}{E_\gamma} \ , \tag{1}$$

where $|q_{\|}|$ is the component of the momentum recoil, $\mathbf{q}$, parallel to the initial electron velocity and the other symbols have their usual meanings. Recall, in a crystal possible values of $\mathbf{q}$ are discrete: $\mathbf{q} = \mathbf{g}$ [7], where $\mathbf{g}$ is a reciprocal lattice vector. The minimal reciprocal lattice vector giving rise to the main CB peak in both the PE

and the SOS orientations is given by

$$|g_{\|}|_{min} = \frac{2\pi}{d}\Theta. \quad (2)$$

For the PE orientation, d is the interplanar distance and $\Theta = \psi$, the electron incident angle with respect to the plane. For the SOS orientation d is the spacing between the axes (strings) forming the planes, and $\Theta = \theta$, the electron incident angle with respect to the axis. The position of the hard photon peak can be selected by simultaneous solution of the last two equations,

$$\Theta = \frac{d}{4\pi\gamma\lambda_c}\frac{E_\gamma}{E_0 - E_\gamma}. \quad (3)$$

With the appropriate choice of $\theta = \Theta$ the intensity of the SOS radiation may exceed the ICB radiation by an order of magnitude.

When a thin silicon crystal is used with an electron beam of energy $E_0 = 178\,\text{GeV}$ incident along the SOS orientation, within the (110) plane and with an angle of $\theta = 0.3$ mrad to the $< 100 >$ axis, the hard photon peak position is expected at $E_\gamma = 129\,\text{GeV}$.

In the current experiment, a 1.5 cm thick silicon crystal was used in the SOS orientation with the electron beam ($E_0 = 178\,\text{GeV}$) incident within the (110) plane with an angle of $\theta = 0.3$ mrad to the $< 100 >$ axis. This gives the hard photon peak position at $x_{max} = 0.725$. This corresponds to the photon energy $E_\gamma = 129\,\text{GeV}$. Under this condition the radiation is expected to be enhanced by about a factor 30 with respect to the ICB for a randomly oriented crystalline Si target.

The coherence length determines the effective longitudinal dimension of the interaction region for the phase coherence of the radiation process:

$$l_{coh} = \frac{1}{|q_{\|}|}. \quad (4)$$

The radiation spectrum with the crystal aligned in SOS orientation has in addition to the CB radiation a strong component at a low energy which is characteristic of PC radiation. As the electron direction lines up with a crystallographic plane in the SOS orientation, the planar channelling condition is fulfilled. For channelling radiation the coherence length is much longer than the interatomic distances and the long range motion, characteristic of planar channelled electrons, becomes dominant over short range variations with the emission of low energy photons. Theoretical calculations [14, 15] predict a more intense soft photon contribution with a high degree of linear polarization of up to 70%.

The simulation of the enhancements of both the low energy and the high energy components of the radiation emission for the SOS orientation under conditions applicable to this experiment are presented in Fig. 1.

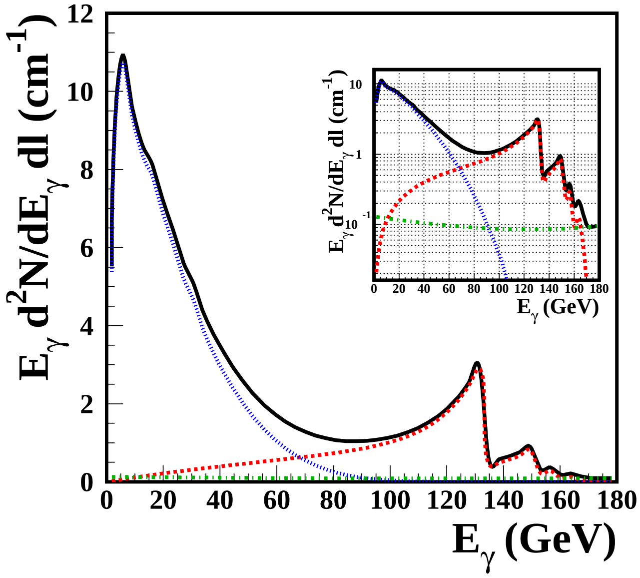

FIG. 1: Photon power yield per unit of thickness, $E_\gamma d^2N/dE_\gamma dl$, for a thin silicon crystal in the SOS orientation for a $E_0 = 178\,\text{GeV}$ electron beam incident within the (110) plane and at an angle of $\theta = 0.3\,\text{mrad}$ to the $< 100 >$ axis. At low energy the PC radiation dominates and at high energies the SOS radiation peaks. The solid curve represents the total of the contributions from (green dash-dotted) ICB, (blue dotted) PC, and (red dashed) SOS radiation. vThe insert is a logarithmic representation and shows the flat incoherent contribution and the enhancement with a factor of about 30 for SOS radiation at 129 GeV.

III. EXPERIMENTAL SETUP

The NA59 experiment was performed in the North Area of the CERN SPS, where unpolarized electron beams with energies above 100 GeV are available. We used a beam of 178 GeV electrons with angular divergence of $\sigma_{x'} = 48\,\mu\text{rad}$ and $\sigma_{y'} = 35\,\mu\text{rad}$ in the horizontal and vertical plane, respectively.

The experimental setup shown in Fig. 2 was also used to investigate the linear polarization of CB and birefringence in aligned single crystals [8, 9]. This setup is ideally suited for detailed studies of the photon radiation and pair production processes in aligned crystals.

The main components of the experimental setup are: two goniometers with crystals mounted inside vacuum chambers, a pair spectrometer, an electron tagging system, a segmented leadglass calorimeter, wire chambers, and plastic scintillators. In more detail a 1.5 cm thick Si crystal can be rotated in the first goniometer with $2\,\mu\text{rad}$ precision and serves as radiator. A multi-tile synthetic diamond crystal on the first goniometer can be rotated with $20\,\mu\text{rad}$ precision and is used as the analyzer of the linear polarization of the photon beam.

The photon tagging system consists of a dipole mag-

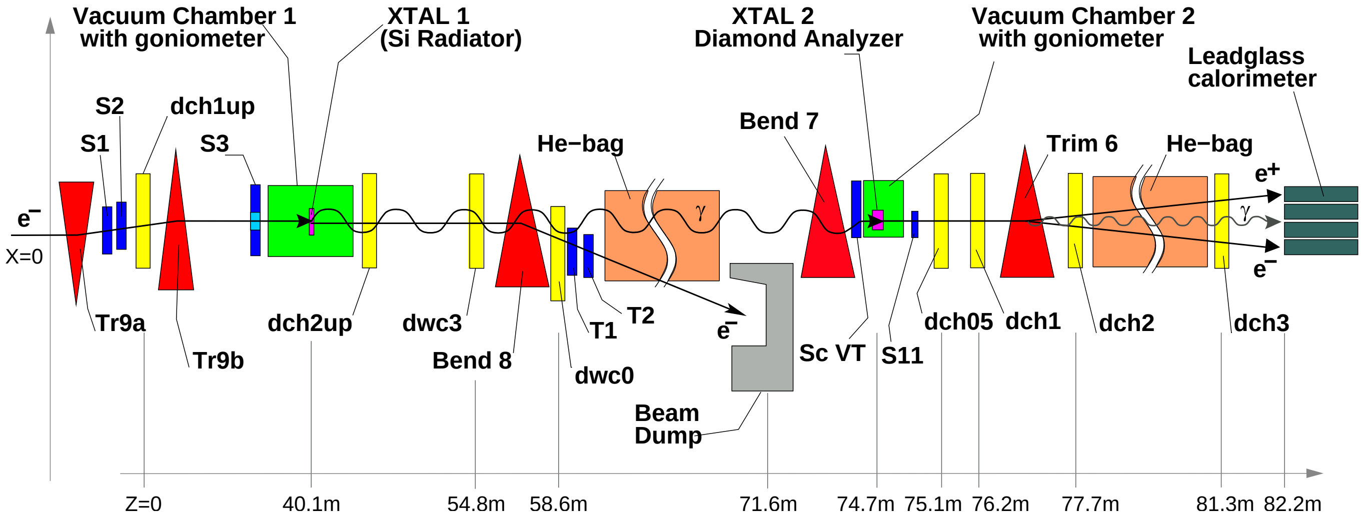

FIG. 2: NA59 experimental setup.

net B8, wire chamber dwc0, and scintillators T1 and T2. Given the geometrical acceptances and the magnetic field, the system, tags the radiated energy between 10% and 90% of the electron beam energy. Drift chambers dch1up, dch2up, and delay wire chamber dwc3 define the incident and the exit angle of the electron at the radiator.

The e^+e^- pair spectrometer consists of dipole magnet Trim 6 and of drift chambers dch05, dch1, dch2, and dch3. The drift chambers measure the horizontal and vertical positions of the passing charged particles with $100\,\mu$m precision. Together with the magnetic field in the dipole this gives a momentum resolution of $\sigma_p/p^2 = 0.0012$ with p in units of GeV/c. The pair spectrometer enables the measurement of the energy of a high energy photon, E_γ, in a multi-photon environment. Signals from the plastic scintillators S1, S2, S3, T1, T2, S11 and veto detector ScVT provide several dedicated triggers.

The total radiated energy E_{tot} is measured in a 12-segment array of leadglass calorimeter with a thickness of 24.6 radiation lengths and a resolution of $\sigma_E = 0.115\,\sqrt{E}$ with E in units of GeV. A central element of this leadglass array is used to map and to align the crystals with the electron beam.

A detailed description of the NA59 experimental apparatus can be found in reference [8].

IV. RESULTS AND DISCUSSION

The experiment can be divided in two parts: (A) production of the photon beam by the photon radiation of the 178 GeV electron beam in the Si radiator oriented in the SOS mode and (B) measurement of the linear polarization by using diamond crystals as analyzers. Prior to the experiment Monte Carlo (MC) simulations were used to estimate the photon yield, the radiated energy, and the linear polarization of the photon beam and we optimized the orientation of the crystal radiator. The MC calculations also included the crystal analyzer to estimate the asymmetry of the e^+e^- pair production. The simulations further included the angular divergence of the electron beam, the spread of 1% in the beam energy, and the generation of the electromagnetic shower that develops in oriented crystals. To optimize the processing time of the MC simulation, energy cuts of 5 GeV for electrons and of 500 MeV for photons were applied.

A. Photon Beam

We used a beam angle of $\theta = 0.3$ mrad to the $\langle 100 \rangle$ axis in the (110) plane of the 1.5 cm thick Si crystal which is the optimal angle for a high energy SOS photon peak at 129 GeV (see Fig. 1). As is mentioned above, the radiation probability with a thin radiator is expected to be 30 times larger at that energy than the Bethe-Heitler (ICB) prediction for randomly oriented crystalline Si.

However, there are several consequences for the photon spectrum due to the use of a 1.5 cm thick crystal For the chosen orientation of the Si crystal, the emission of mainly low energy photons from planar coherent bremsstrahlung (PC) results in a total average photon multiplicity above 15. And the most probable radiative energy loss of the 178 GeV electrons is expected to be 80%. The beam energy decreases significantly as the electrons traverse the crystal. The peak energy of both SOS and PC radiation also decreases with the decrease in electron energy. Consequently, the SOS radiation spectrum is not peaked at the energy for a thin radiator, but becomes a smooth energy distribution. Clearly, many electrons may pass through the crystal without emitting SOS radiation and still lose a large fraction of their energy due to PC and ICB. Hard photons emitted in the first part of the crystal that convert in the later part do not contribute anymore to the high energy part of the photon spectrum. A full Monte Carlo calculation is nec-

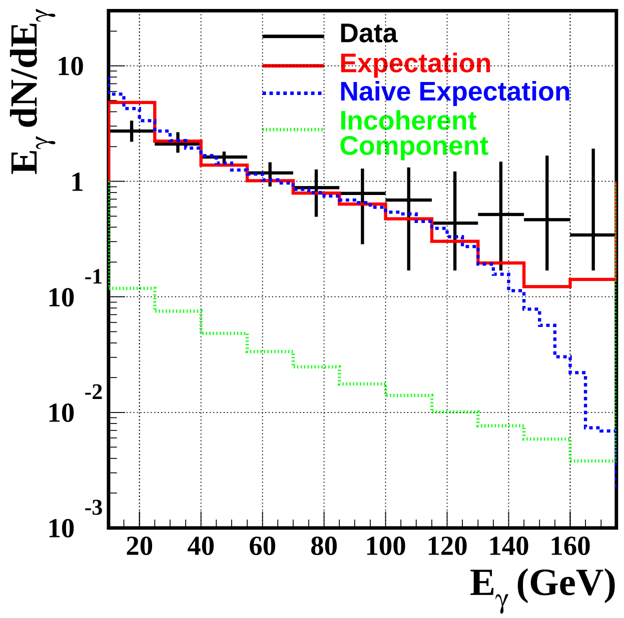

FIG. 3: Photon power yield, $E_\gamma dN/dE_\gamma$, as a function of the energy E_γ of individual photons radiated by an electron beam of 178 GeV in the SOS-aligned 1.5 cm Si crystal. The black crosses are the measurements with the pair spectrometer, the vertical lines represent the errors including the uncertainty in the acceptance of the spectrometer. The (red solid) histogram represent the MC prediction for our experimental conditions. The (green dotted) represent the small contribution due to incoherent interactions. For completeness, we also show the theoretical predictions if the experimental effects are ignored (blue dashed).

essary to propagate the predicted photon yield with a thin crystal, as shown in Fig. 1 for 178 GeV electrons, to the current case with a 1.5 cm thick crystal.

This has been implemented for the measured photon spectrum shown in Fig. 3. We see that the measured SOS photon spectrum shows a smoothly decreasing distribution. The low energy region of the photon spectrum is especially saturated, due to the abundant production of low energy photons. Above 25 GeV however, there is satisfactory agreement with the theoretical Monte Carlo prediction, which includes the effects mentioned above.

The enhancement of the emission probability compared to the ICB prediction is given in Fig. 4 as a function of the total radiated energy as measured in the calorimeter. The maximal enhancement is about a factor of 18 at 150 GeV and corresponds well with the predicted maximum of about 20 at 148 GeV. This is a multi-photon spectrum measured with the photon calorimeter. The peak of radiated energy is situated at 150 GeV, which means that each electron lost about 80% of its initial energy due to the large thickness of the radiator. This means that the effective radiation length of the oriented single crystal is several times shorter in comparison with the amorphous target. The low energy region is depleted due to the pile-up of several photons.

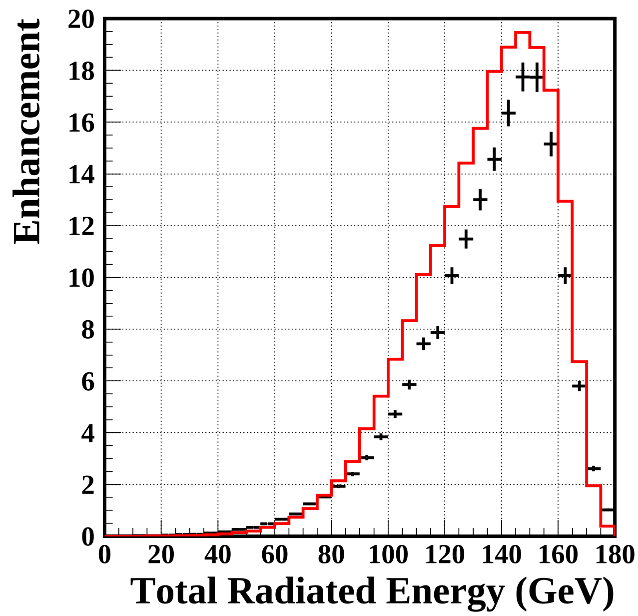

FIG. 4: Enhancement of the intensity with respect to the Bethe-Heitler (ICB) prediction for randomly oriented polycrystalline Si as a function of the total radiated energy E_{tot} in the SOS-aligned Si crystal by 178 GeV electrons. The black crosses are the measurements and the red histogram represent the MC prediction.

The expected linear polarization is shown in Fig. 5 as a function of photon energy. It is well known that channelling radiation in single crystals is linearly polarized [16, 17] and the low energy photons up to 70 GeV are also predicted to be linearly polarized in the MC simulations. High energy photons are predicted with an insignificant polarization.

B. Asymmetry Measurement

In this work, the photon polarization is always expressed using the Stoke's parametrization with the Landau convention, where the total elliptical polarization is decomposed into two independent linear components and a circular component. In mathematical terms, one writes:

$$P_{\text{linear}} = \sqrt{\eta_1^2 + \eta_3^2}, \quad P_{\text{circular}} = \sqrt{\eta_2^2}, \quad P_{\text{total}} = \sqrt{P_{\text{linear}}^2 + P_{\text{circular}}^2} \quad . \tag{5}$$

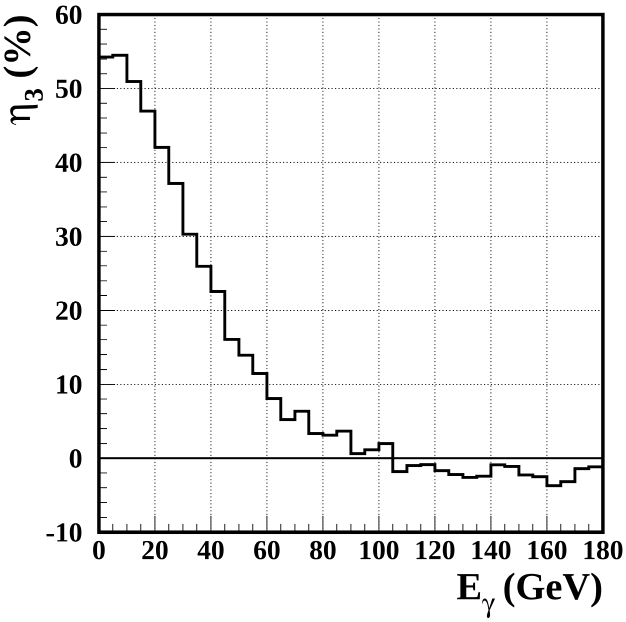

FIG. 5: Expected linear polarization as a function of the energy E_γ of the photons produced in the SOS-aligned Si crystal by 178 GeV electrons.

The radiator angular settings were chosen to have the total linear polarization from the SOS radiation purely along η_3, that is $\eta_1 = 0$. The η_2 component is also zero because the electron beam is unpolarized. The expected η_3 component of the polarization shown is in Fig. 5.

In order to determine the linear polarization of the photon beam the method proposed in reference [18] with an oriented crystal was chosen. This method of measurement of the linear polarization of high energy photons is based on coherent e^+e^- pair production (CPP) in single crystals which depends on the orientation of the reciprocal lattice vector and the linear polarization vector. Thus, the dependence of the CPP cross section on the linear polarization of the photon beam makes an oriented single crystal suitable as an efficient polarimeter for high energy photons.

The basic characteristic of the polarimeter is the analyzing power R of the analyzer crystal [18]. By choosing the appropriate crystal type and its orientation a maximal analyzing power can be obtained. The relevant experimental quantity is the asymmetry A of the cross sections $\sigma(\gamma \to e^+e^-)$ for parallel and perpendicular polarization, where the polarization direction is defined with respect to a particular crystallographic plane of the *analyzer* crystal. This asymmetry is related to the linear polarization of the photon beam, $P_{\rm linear}$, through:

$$A \equiv \frac{\sigma(\gamma_\perp \to e^+e^-) - \sigma(\gamma_\parallel \to e^+e^-)}{\sigma(\gamma_\perp \to e^+e^-) + \sigma(\gamma_\parallel \to e^+e^-)} = R \times P_{\rm linear}. \quad (6)$$

The analyzing power R corresponds to the asymmetry expected for photons that are 100% linearly polarized perpendicular to the chosen crystallographic plane.

Denoting the number of e^+e^- pairs produced in perpendicular and parallel cases by p_1 and p_2, and the number of the normalisation events in each case by n_1 and n_2, respectively, the measured asymmetry can be written as:

$$A = \frac{p_\perp/n\perp - p_\parallel/n_\parallel}{p_\perp/n_\perp + p_\parallel/n_\parallel}, \quad (7)$$

where p and n are acquired simultaneously and therefore correlated. Further details of this method, as well as refinements to enhance the analyzing power R by using kinematic cuts on the pair spectra, may be found in reference [8].

The existence of a strong anisotropy for the channelling of the e^+e^- pairs during their formation is the reason for the polarization dependent CPP cross section of photons passing through oriented crystals. This means that perfect alignment along a crystallographic axis is not an efficient analyzer orientation due to the approximate cylindrical symmetry of the crystal around atomic strings. However, for small angles of the photon beam with respect to the crystallographic symmetry directions the conditions for the formation of the e^+e^- pairs prove to be very anisotropic. As it turns out, the orientations with the highest analyzing power are those where the e^+e^- pair formation zone is not only highly anisotropic but also inhomogeneous with maximal fluctuations of the crystal potential along the electron path. At the crystallographic axes the potential is largest and so are the fluctuations. These conditions are related to the ones of the SOS orientation: (i) a small angle to a crystallographic axis to enhance the pair production (PP) process by the large fluctuations and (ii) a smaller angle to the crystallographic plane to have a long but still anisotropic formation zone for CPP.

In the NA59 experiment we used a multi-tile synthetic diamond crystal as an analyzer oriented with the photon beam at 6.2 mrad to the $\langle 100 \rangle$ axis and at 465 μrad from the (110) plane. This configuration is predicted to have a maximal analyzing power for a photon energy of 125 GeV as is shown in Fig. 6. The predicted analyzing power in the high energy peak region is about 30%.

The measured asymmetry and the predicted asymmetry are shown in Fig. 7. One can see that the measured asymmetry is consistent with zero over the whole photon energy range. For the photon energy range of 100-155 GeV we find less than 5% polarization at 0.9 confidence level. The null result is expected to be reliable as the correct operation of the polarimeter had been confirmed in the same beam-time in measurements of the polarisation of CB radiation [8]. Note, that the expected asymmetry is small, especially in the high energy range of 120-140 GeV, where the analyzing power is large, see Fig. (6). This corresponds to the expected small linear polarization in the high energy range, see Fig. (5).

In contrast to the result of a previous experiment [6], our results are consistent with calculations that predict negligible polarization in the high energy photon peak

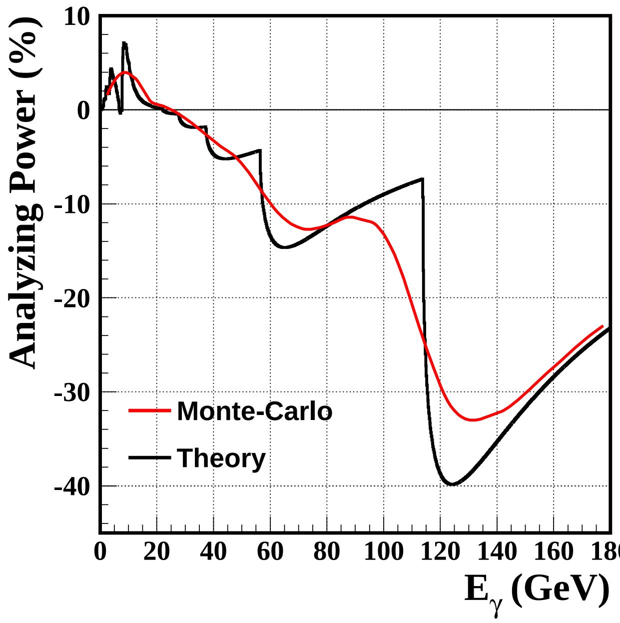

FIG. 6: Analyzing power R with the aligned diamond crystal as a function of the photon energy E_γ (black curve) for an ideal photon beam without angular divergence and (red curve) for the Monte Carlo simulation of photons with the beam conditions in the NA59 experiment.

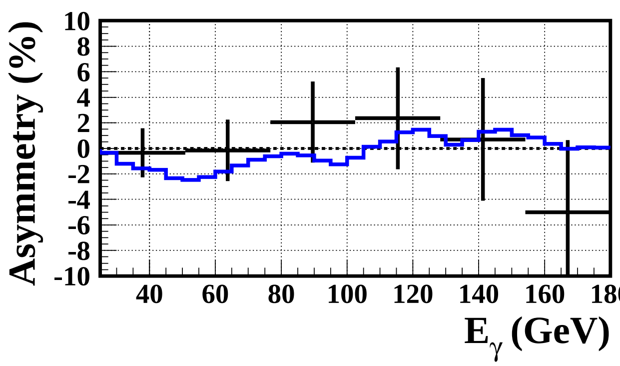

FIG. 7: Asymmetry of the e^+e^- pair production in the aligned diamond crystal as a function of the photon energy E_γ which is measured to determine the P_1 component of the photon polarization in the SOS-aligned Si crystal by 178 GeV electrons. The black crosses are the measurements and the red histogram represent the MC prediction.

for the SOS orientation. The analyzing power of the diamond analyzer crystal in the previous experiment's [6] setup peaked in the photon energy range of 20-40 GeV where a high degree of linear polarization is expected. But in the high energy photon region we expect a small analyzing power of about 2-3%, also following recent calculation [13, 14]. The constant asymmetry measured in a previous experiment [6] over the whole range of total radiated energy may therefore not be due to the contribution of the high energy photons.

From Fig. 5 one can expect a large linear polarization for photons in the low energy range of 20-50 GeV. However, the analyzing power was optimized for an photon energy of 125 GeV and is small in the region where we expect a large polarization. A different choice of orientation of the analyzer crystal can move the analyzing power peak to the low energy range and may be used to measure the linear polarization in the low energy range.

V. CONCLUSION

We have performed an investigation of both enhancement and polarisation of photons emitted in the so called SOS radiation. This is a special case of coherent bremsstrahlung for multi-hundred GeV electrons incident on oriented crystalline targets, which provides some advantages comparing with other types of CB orientations. The experimental set-up had the capacity to deal with the relatively high photon multiplicity and single photon spectra were measured. This is very important in view of the fact that there are several production mechanisms for the multiphotons, which have different radiation characteristics.

We have confirmed the single photon nature of the hard photon peak produced in SOS radiation.

The issue of the polarisation of the SOS photons had previously not been conclusively settled. Earlier results in a previous experiment [6] had indicated that a large polarization might be obtained for the high energy SOS photons. Our experimental results show that the high energy photons emitted by electrons passing through the Si crystal radiator oriented in the SOS mode have a linear polarization smaller than 20% at a confidence level of 90%.

Since the previous experiments, the theoretical situation for the polarisation of hard SOS photons has also become clearer. Our results therefore also confirm recent calculations which predict that the linear polarization of high energy photons created in SOS orientation of the crystal is small compared to the polarization obtained with the PE orientation.

Photon emission by electrons traversing single crystals oriented in the SOS orientation has interesting peculiarities since three different radiation processes are involved: (1) incoherent bremsstrahlung, (2) channelling radiation, and (3) coherent bremsstrahlung induced the periodic structure of the atomic strings in the crystal that are crossed by the electron. The calculations presented here have taken these three processes into account, and predict around a 5% polarization for the high energy SOS photons. This prediction is consistent with our null polarization asymmetry measurement for the single photons with energies above 100 GeV.

Acknowledgments

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